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A STUDY OF BOILING HEAT TRANSFER AS APPLIED TO THE COOLING OF BALL BEARINGS IN THE HIGH PRESSURE OXYGEN TURBOPUMP OF THE SPACE SHUTTLE MAIN ENGINE

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ABSTRACT

Two sets of ball bearings support the main shaft within the High Pressure Oxygen Turbopump (HPOTP) in the Space Shuttle's Main Engine (SSME). In operation, these bearings are cooled and lubricated with high pressure liquid oxygen (LOX) flowing axially through the bearing assembly. Currently, modifications in the assembly's design are being contemplated in order to enhance the lifetime of the bearings and to allow the HPOTP to operate under larger loads. An understanding of the fluid dynamics and heat transfer characteristics of the flowing LOX is necessary for the implementation of these design changes.

In light of the large amounts of heat being generated at the bearing/race contact of the rapidly rotating shaft, the heat transfer mode of boiling must be considered. Because of the high stresses and large speeds associated with the bearing assembly, direct experimental observation of the heat transfer process is exceptionally difficult. The use of numerical analysis, therefore, is being studied for its ability to yield useful predictions of the heat transfer process. The proposed computational model of the LOX fluid dynamics, in addition to dealing with a turbulent flow in a complex geometry, must address the complication associated with boiling and two-phase flow.

In the present report, the feasibility of and possible methods for modeling boiling heat transfer are considered. The theory of boiling as pertains to this particular problem is reviewed. The report gives recommendations for experiments which would be necessary to establish validity for correlations needed to model boiling.

INTRODUCTION

Figure 1 (1) is a schematic which depicts the HPOTP ball bearing assembly. LOX flows axially through the rapidly rotating balls to cool and lubricate the bearings. A high rate of local heat generation is expected to precipitate boiling at the surfaces of the assembly. Boiling can affect the heat transfer from the solid surface to the free stream LOX in either of two ways depending on the boiling mechanism, nucleate or film.

Nucleate boiling is associated with high heat transfer rates. With only a small increase of surface temperature, the heat transfer due to nucleate boiling may increase by more than an order of magnitude over that due to single-phase forced convection. With a further increase in heat flux from the surface, however, the boiling mechanism may change from nucleate to film boiling. This transition occurs as a discontinuity or catastrophe; a small increase in heat flux beyond the critical point produces a huge increase in the surface temperature. As illustrated in figure 2 (2), high surface temperatures are required to sustain film boiling. As a mechanism for cooling the bearing assembly, therefore, nucleate boiling may be considered advantageous and film boiling deleterious.

With boiling, large gradients in temperature as a function of heat flux make the accurate computer modeling of heat transfer a formidable task. The location of the aforementioned transition points as well as the magnitude of temperature as a function of heat flux is critical to the attainment of a representative solution.

A large quantity of literature exists concerning both theoretical and experimental research in boiling heat transfer. These studies have focused, however, almost exclusively on flows through uniformly heated pipes and, to a lesser degree, on flows along heated rod bundles. The correlations necessary to affect closure for boiling and two-phase flow associated with more general flow situations are few in number and vague in applicability.

The lack of sound theory and of general purpose correlation equations coupled with the erratic nature of the boiling process indicate that the creation of a numerical model to represent accurately the heat transfer and fluid flow in the HPOTP's bearing assembly would be extremely challenging.
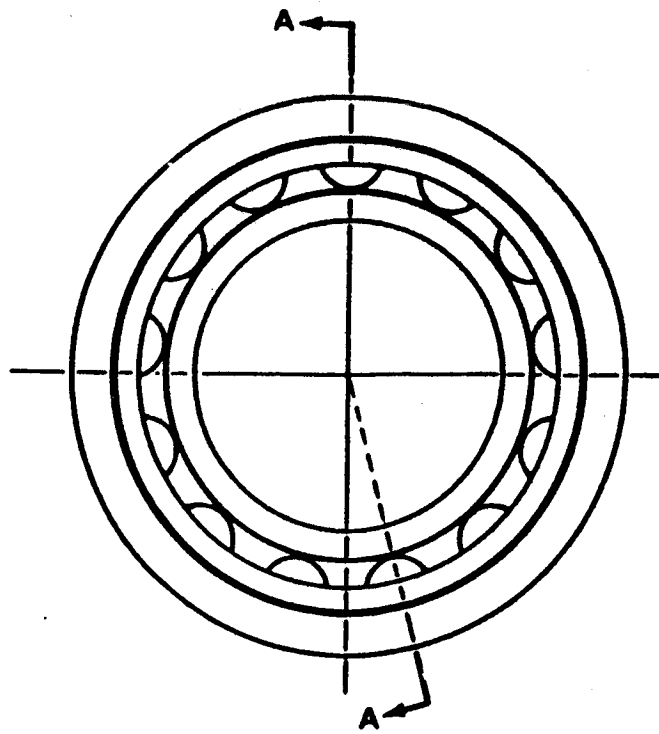
Front view
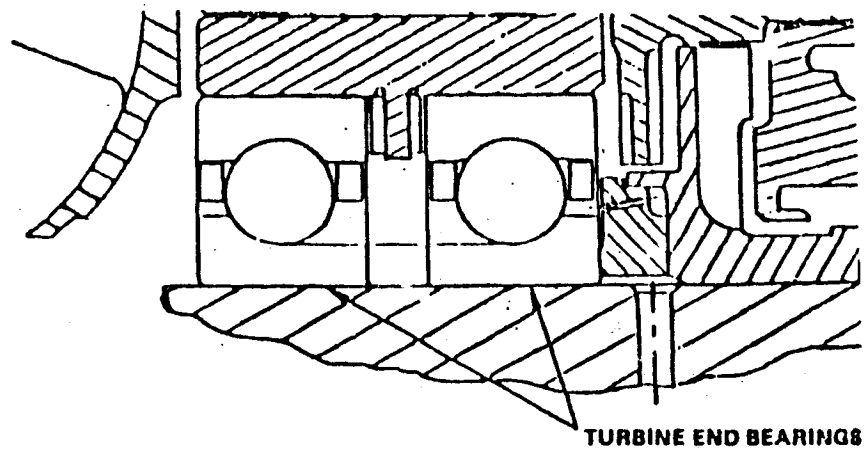
Side view

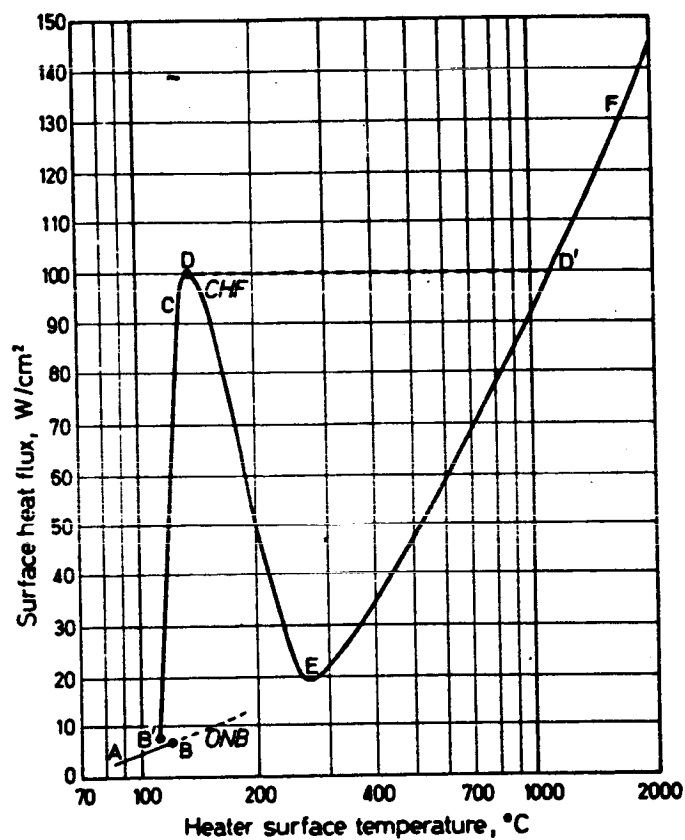Figure 1.   Ball Bearing Assembly in the HPOTP

Figure 2. The Boiling Curve, water at 1 atmosphere.

This report discusses several aspects of boiling heat transfer as it might apply to the cooling of the HPOTP bearing assembly. The first section will describe the boiling curve and the relationship between surface temperature and heat flux associated with boiling. A brief discussion of the physical theory of boiling will constitute the second section. Section three will concern the translation of the physical phenomena encountered in boiling and two-phase flows into the appropriate mathematical representations and the numerical solution of those equations. The fourth section will discuss the experimental investigation necessary to determine proper correlation equations for represention of boiling and two-phase flow.

OBJECTIVES

1) To review the literature concerning forced convection boiling heat transfer and two phase flow.

2) To determine the feasibility of numerically modeling boiling and two phase flow in conjunction with LOX flow in the HPOTP ball bearing assembly.

3) To determine the best means and the most appropriate correlation equation to affect this modeling.

4) To numerically model boiling heat transfer in the forced convection of flow through a two-dimensional curved channel and to compare the results with experimental results.

SECTION I: THE BOILING CURVE

The boiling curve presents a comprehensive representation of the heat transfer associated with boiling. The various regimes of boiling are represented as separate sections of the curve. The boiling curve shown in Figure 2 has as its abscissa, T_w, the wall temperature, and as its ordinate,

$q_w"$, the value of the wall heat flux, a function of

temperature.

The boiling curve in Figure 2 is that for water at atmospheric pressure over a heated horizontal flat plate. The line from A to B represents the heat transfer due to single-phase natural convection. When the temperature reaches point B, there occurs the onset of nucleate boiling, ONB, at which occurrence the heat flux experiences a discontinuous increase while the surface temperature takes a discrete drop to point B'. Note that ONB takes place at a temperature well above that of the saturation temperature. T_{SAT}, the temperature difference

between the wall and the saturation temperature depends on the conditions of the solid surface, particularly roughness. Surface tension of the liquid-vapor mixture plays an important role in the mechanism of ebullition, the inception of boiling.

In the nucleate boiling range, from B' to C, a small increase of surface temperature causes a large increase in heat flux. At the temperature for point D, however, the

curve experiences a sudden reversal. The curve's maximum, the point D, is named the critical heat flux, CHF, and represents the most important point with regard to the present problem.

Between the points D and E, the transition zone, further increases in surface temperature yield decreases in heat flux. The mode of boiling is changing from nucleate to film. At point E the surface is covered entirely by a vapor film whose heat transfer capacity is far lower than that for nucleate boiling. As the temperature is increased from the point E, the modes of heat transfer are essentially those of single phase conduction, convection and radiation through the vapor film.

In most boiling problems of practical interest, the boiling curve is best represented with the heat flux as the independent variable. In this orientation, it is noted that the solid curve in Figure 2 no longer represents a mathematically homogeneous function; consequently, its represention of the heat transfer is altered.

With the heat flux as the dependent variable, the CHF is characterized by a catastrophic increase in temperature (D-D') as the value of heat flux is raised further. The boiling mechanism experiences a discrete jump from the nucleate to the film regime. If the heat flux is decreased from, say, point F the transition will follow the curve FD'E in the film boiling regime. At point E, the Leidenfrost point, the wall temperature will experience a catastrophic drop to the corresponding heat flux on curve B'C.

In the flow field about a blunt object like one of the HPOTP's ball bearings, one can expect a variable pressure field. The two-dimensional boiling curve which is applicable at a single pressure would be replaced by a three dimensional boiling surface. The surface temperature depends on pressure as well as heat flux in a flow situation involving a variable pressure field.

SECTION II: THE PHYSICS OF BOILING

References 3-14 represent a few examples of the numerous investigations into the theory of boiling. While theoretical investigations have led to better understanding of the basic physics underlying boiling, the correlations used to model boiling heat transfer stem in

large part from the appropriate parameterization of experimental observations. As previously mentioned, almost all the experimental work in forced convective boiling heat transfer concerns the most elementary hydrodynamic situation, flow through straight circular pipes.

A study of the theory of boiling is useful for obtaining an appreciation of the interrelationship of factors upon which the boiling process depends. Particularly crucial to this process is the effect of the surface condition. In the complicated flow situation of the present problem, the hydrodynamics and heat transfer may depend heavily on the condition of the surface.

The theory of nucleation and the solid-liquid-vapor relationship of boiling is addressed in references 3-12. These authors attempt to explain how the surface temperature for nucleation relates to the composition of the solid surface.

Several correlations for the heat transfer coefficient due to pool boiling have been determined from a combination of theory and experiments. These formulations, as a rule, require accurate physical property values, are complicated to evaluate, and contain inherent uncertainty since the conditions of the surface are ignored.

Using the law of corresponding states, however, Borishanski (13) has formulated an expression which is considerably more simple to apply to describe the heat transfer coefficient for pipe flow boiling

$$h = A^* q_w^{"0.7} F(p)$$

Mostinski (14) proposed the following expressions for A^* and $F(p)$:

$$A^* = 0.1011 \ P_{cr}^{0.69}$$

$$F(p) = 1.8 \ P_r^{0.17} + 4 \ P_r^{1.2} + 10 \ P_r^{10}$$

where P_r is the reduced pressure and P_{cr} is the critical pressure for the fluid, and $q_w^{"}$ is the heat flux at the wall.

SECTION III: THE MATHEMATICS AND NUMERICAL MODELING OF BOILING

The accurate computation of a convective heat transfer problem requires the correct mathematical interpretation of the physics governing the particular flow field. Typically, the resulting equations represent a trade-off between exactness and tractability. The choice of a mathematical representation is particularly critical in a complex flow such as that of LOX in the HPOTP's bearing assembly.

For fluid mechanics problems involving two-phase flow, several authors have addressed the problem of the optimum equations needed for predicting the flow field. Concerning this question, three sources which have been found particularly illustrative are Chawla (15), Ishii (16,17,18) and Bergles (19). These sources contain theoretical discussion as well as some specific correlation equations.

Basically two different approaches to formulating problems of two-phase flow exist: mixture models and two-fluid models. The more tractable of the two, the mixture model, treats the two-phase flow as a one-phase flow with varying fluid properties. The set of governing equations for the second fluid is thereby eliminated.

As a substitute for the neglected equations, the mixture model employs constitutive laws to model two-phase phenomena such as boundary slippage. This model is basically limited to finely-dispersed two-phase flows. Only when the flow consists of a fairly homogeneous vapor-liquid mixture can the numerical simulation of the mixture model be said to represent accurately the two-phase flow.

The balls in the bearing assembly are rotating and moving with respect to the incoming LOX at a high rate. In the nucleate boiling regime, the churning of fluid by the rapidly moving balls can be expected to homogenize effectively the two phases (20). The mixture model is suitable for modeling the two-phase flow in this situation.

Since it is more general in its applicability, the two-fluid model requires more computational effort to solve. In the two-fluid model, the two phases are described individually; consequently, separate sets of equations are necessary for each phase.

The actual two-phase flow is unsteady. To eliminate the complication of small scale time-dependency, the representative equations must be time-averaged to some degree. This averaging process introduces the necessity of modeling the time-dependent effects which have been eliminated with the averaging.

Parallels may be drawn between turbulent and two-phase flows. Both can, at best, be considered quasi-steady state, and both require time-averaging combined with correlation models before solution of a representative flow field may be attempted. In the case of two-phase flows, however, a further complication arises in the form of the presence of surface tension.

The property of interfacial surface tension, upon which a two-phase flow is heavily dependent, is unaccounted for in the Navier-Stokes, energy, and continuity equations. Constitutive equations are required to model transfer at the interface between phases (jump condition). Even if the problem of the fully time-dependent equations describing two-phase flow were tractable, the solution would require that surface tension effects be modeled.

In the problem of LOX flow through the HPOTP's bearings, the spatial distribution of boiling regimes will not be known a priori. Delhaye (21) points out that in two-phase flow, the flow patterns must have been predetermined in order to model the physical phenomenon as closely as possible. It is felt, therefore, that detailed experiments of flows which match certain aspects of the LOX bearing flow field will be necessary in order to understand the basic nature of the flow and to develop correlation equations. These experiments would need to include boiling combined with hydrodynamic separation, and rotating boundaries.

The transition from nucleate to film boiling may be considered to be the effect of a combination of hydrodynamic cavitation and thermodynamic vaporization. Cavitation arises from the severe pressure gradients of flow around a sphere while vaporization is a function of the high heat flux at the fluid-surface interface. These two phenomena are strongly coupled at the transition point.

With the transition to film-boiling, thermodynamic equilibrium between the phases can no longer be considered valid. The degree of equilibrium depends upon the rate of

transfer at the interfaces between the two phases and upon the typical value of each phase's surface to volume ratio. The heat transfer at the liquid-vapor interface occurs at a slow rate relative to the temperature changes in the rapidly expanding vapor in the region of cavitation. The discrete temperature difference at the interface between the phases, consequently, results in local irreversibil-ilities that prevent thermodynamic equilibrium.

Modeling accurately the two-phase flow in which equilibrium cannot be assumed dictates that the constitutive equations describing transport between the two-phase jump conditions be extremely reliable. This accuracy can be obtained only if the correlation equations are compared with experiments which have characteristics similar to those of the simulated flow.

Likewise, the conditions at which the transition to film-boiling takes place are also critical to a numerical model. At this transition the regimes of boiling, two-phase flow, and, consequentially, heat transfer change dramatically. The parametric values and their interrelationships at which this transition occurs can be known only through experimentation.

To model the film-boiling regime, a numerical simulation which incorporates the two-fluid model would be necessary. As the physical nature of the flow has suffered a severe transition so must the character of the numerical simulation reflect and be able to model this change.

Once the conditions necessary for transition to film-boiling have been established through expe.imenta-tion, a dual-model numerical simulation could be devised. To simulate the flow associated with the nucleate-boiling regime, the mixture model can be used. In the film-boiling regime, the mixture model will no longer be sufficient to describe the two-phase interaction; the greater generality provided by the two-fluid model will be required.

As pertains to the design of the HPOTP's bearing assembly, however, modeling the film-boiling regime may be unnecessary. The essential nature of film-boiling can be known from the boiling curve. The catastophic nature of this curve dictates that surface temperatures at heat fluxes greater than the critical heat flux become extreme. Bearing damage can be expected in the presence of the high temperatures and lack of liquid lubrication associated with film-boiling. The determination of the conditions

for the boiling crisis's inception, therefore, would provide sufficient evidence of the bearing assembly's allowable thermal load.

Previous work in numerically modeling boiling heat transfer has focused on the flow of two-phase fluids through pipes or along rod bundles. In forced convective boiling heat transfer problems such as these, one way to predict local heat transfer rates involves the superposition of the single-phase forced convection curve with the fully developed boiling curve. (See figure 3 from reference 2.) Bowring (22) and Rohsenow (23) have each developed empirical solution procedures to effect this superposition for the flow of fluid through circular, uniformly heated pipes.

This superposition of the two heat transfer modes, convection and boiling, represents a limited range of the boiling curve. For wall temperatures smaller than $T_{WALL,ONB}$ the heat transfer mechanism is solely that of single-phased force convection. For temperatures larger than $T_{WALL,FDB}$, the mechanism may be considered to be that

of fully-developed boiling, F.D.B. (2). In F.D.B., the heat transfer effect of convection is insignificant compared to that of boiling. Beyond $T_{WALL,FDB}$, therefore,

the amount of heat transfer is the same as that of pool boiling.

Since the flow field in a pipe will experience a relatively small pressure variation, the temperature in the F.D.B. curve may be approximated as a function of heat flux only. For a flow over a blunt body, the pressure on the body's surface will show appreciable variation in pressure. The temperature for the more general flow field, therefore, will depend on pressure as well as heat flux, and the fully-developed boiling will be represented by a mathematical surface instead of a curve.

That the correlation equations which serve for boiling and two-phase phenomena in pipe flow would yield accurate results in a more general situation is dubious. New correlation equations to fit more closely the LOX hydrodynamics of the HPOTP bearing problem should be developed from the results of experiments which incorporate the salient features of the actual problem.
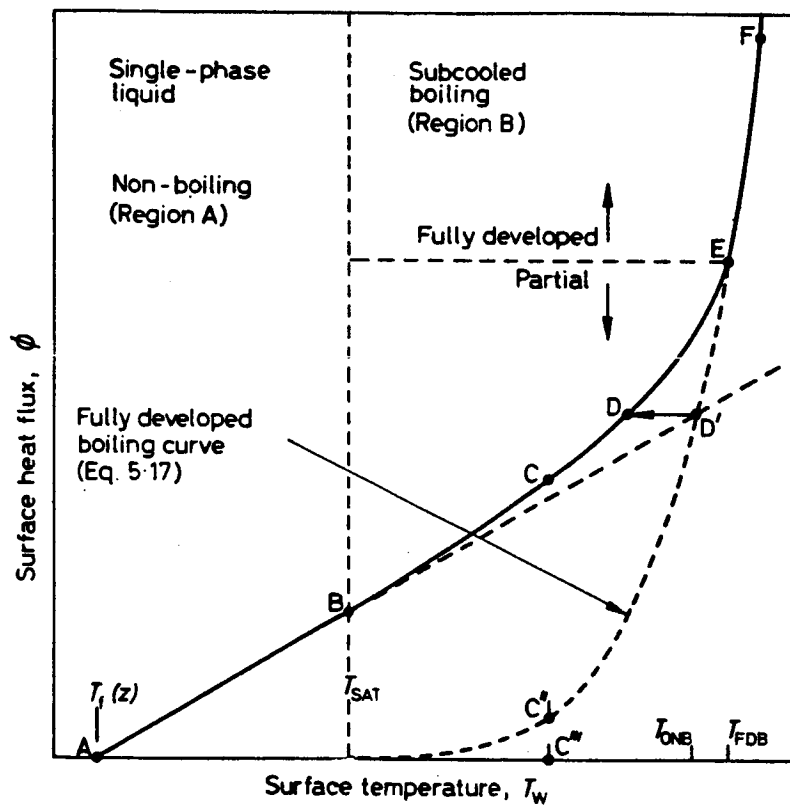
Figure 3.   The Boiling Curve for
            Forced Convection Boiling.

SECTION IV: USEFULNESS OF EXPERIMENTAL INVESTIGATION

In the first three sections of this report, the requirement for experiments as a means to study boiling heat transfer may be summarized by three reasons:

(1) Correlation equations for boiling and two-phase phenomena appropriate to this particular problem do not currently exist.

(2) There needs to be a way to test a code which models this flow by comparing its results with those derived from experimentation.

(3) Experiments involving convective boiling which measure such quantities as heat transfer, quality, and velocity in flow fields that contain the salient features of the LOX flow in the HPOTP will yield information from their physical results. These results may serve in their own right as indicators of design modifications to improve the heat transfer in the HPOTP bearing assembly.

Such experiments should measure local quantities. Previous experimentation in the area of convective boiling heat transfer has been concerned with either pipe flow (24, 25) or external flows in which only global parameters were measured (26, 27). Local heat transfer could be measured using the experimental technique as described by Pais (28).

Experimentation utilizing a variety of fluids would yield non-dimensionalized correlation equations which include the effects of fluid properties.

An experimental study in conjunction with a numerical simulation should begin at an elementary level and progress to higher levels of complexity. At the first level, the flow around a sphere with boiling would be investigated. Several different fluids including water would be used for this study in an effort to determine the effect of fluid properties on the flow and heat transfer. Min (29) has described the apparatus used to recirculate fluids at elevated pressures for boiling studies. Unger (30) has studied the heat transfer effects due to pool boiling of heated spheres quenched in a variety of different fluids.

After the completion of the first level of experimentation the rest of the experimental study would use Freon 113 (T_{SAT} = 46°C at one atmosphere) as the test fluid,

since it remains in the liquid state at one atmosphere and ambient temperatures. Boiling studies which utilize cryogenic fluids must be performed under pressurization. Experimental study beyond the first level would require the study of submerged rotating spheres and moving walls and would be greatly complicated if a high pressure were required in the boiling test section. Experimentation at the first level, on the static sphere, using a variety of fluids, would serve to establish fluid property effects which could be used for the remainder of the experiments.

Progression of the study beyond the first level would involve both experimentation and computation. These studies would involve rotating spheres, rotating spheres enclosed between two static walls, and finally rotating spheres enclosed between moving walls. At each successively more complex level of experimentation, the computer program should be altered to include the sophistication necessary to simulate the next level of experimental reults. In this manner the numerical analysis always can be tested against experiment, while the effect on the mathematical correlations of changing the problem's geometry may be studied.

One design change in the bearing assembly to be considered is that of altering the entry point of the LOX into the assembly (31). Presently the LOX enters the assembly from one end in an axial direction after traversing a torturous path from the shaft's center. The alteration would have the LOX entrance into the bearing assembly located in the shaft between the two sets of balls.

The reasoning behind this alteration is twofold. If the LOX enters into the bearing assembly in a direction radially outward from the axis of rotation, its pressure will be higher. The increased pressure would result from centripetal force as well as from a shorter path with less head loss. As the second reason for such an alteration, the LOX would seem to suffer less chance to experience film boiling since it would impinge against the balls on their open sides and exit from the channeled side. The channeled exit would discourage the cavitation that might be expected with the flow in the wake of a blunt body.

Heuristic reasoning such as that stated above could be demonstrated as correct or incorrect with the use of experiments. While the possibility to conduct experiments which incorporate simultaneously all apsects or the LOX/bearing flow does not exist, the results of

experiments which contain some aspects of the flow might
be extrapolated to yield noteworthy indicators.

CONCLUSIONS AND RECOMMENDATIONS

Following an extensive literature search into convective boiling heat transfer and two-phase flow, two broad conclusions have been reached.

1) While an accurate computer simulation of the LOX flow in the HPOTP ball bearing assembly is feasible, this goal cannot be achieved unless suitable correlation equations applicable to the conditions of this problem are determined.

2) Experiments are needed for the development of correlation equations, testing of the numerical model and as a direct source of information concerning the physics of the problem.

The numerical model stated as an objective has not been programmed. While the computer code PHOENICS (29) was used on some simple pipe flow cases, the lack of valid empirical correlation prevented the demonstration of boiling characteristics which might be found in a curved channel.

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